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PROPERTIES OF PERIFERAL NERVE EXCITATION IN RESPECT OF LOCATION OF COIL FOR MAGNETIC NERVE STIMULATION

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Abstract- **In the magnetic stimulation of the peripheral nerve fiber with the figure-of-eight coil, the nerve fiber beneath the figure-of-eight coil is considered to be stimulated with the lowest intensity when it is parallel to the junction of the figure-of-eight coil. However, some experimental studies with the magnetic peripheral stimulation showed that the large compound muscle action potential is elicited with the figure-of-eight coil oriented in the other directions. In the present study, we try to explain the cause of such a discrepancy with the analysis of the model of the magnetic nerve stimulation, and confirm the validity of the result obtained from the model analysis by the experimental study of the magnetic peripheral nerve stimulation. We show that the threshold for the nerve excitation become lowest not only when the junction of the figure-of-eight coil is parallel to the nerve fiber but also when that is perpendicular to the nerve fiber.**
***Keywords* - magnetic stimulation, peripheral nerve, figure-of-eight coil, threshold for nerve excitation**

I. INTRODUCTION

Magnetic stimulation of the nervous system by using strong magnetic field pulse has excellent advantages such as non-invasive nature and ability to stimulate a deep region.

A figure-of-eight coil has been developed for the focal magnetic stimulation. Eddy currents induced by opposite magnetic fields are gathered just below the center of the figure-of-eight coil. The figure-of-eight coil is used commonly in magnetic nerve stimulation.

Despite the usefulness of the magnetic stimulation as a clinical tool, the mechanisms of activation of nerve fiber elicited in the magnetic stimulation are still not well understood. Analysis of the numerical model indicated that action potential is generated in a nerve fiber at the negative peak of the activating function: spatial derivative of induced electrical field along the nerve fiber. There are experimental studies concerning the magnetic stimulation of peripheral nerve by using the figure-of-eight coil. Although most of them showed that the nerve fiber excites with the lowest intensity when the nerve fiber is parallel to the junction of the figure-of-eight coil, some reports indicated that the nerve fiber does so when it is in the other direction.

In the present study, we tried to explain the cause of such a discrepancy. Using a numerical model of nerve fiber, we analyzed the stimulated site and stimulating threshold for nerve excitation especially focused on the location of the figure-of-eight coil, and carried out the experimental study of the magnetic peripheral nerve stimulation in order to confirm the validity of the result obtained from the model analysis.

II. METHODS

A) *Theoretical Calculation*

1) *Calculation of Induced Electric Field and Activating Function*: A figure-of-eight coil is located in an infinite medium as shown in Fig. 1. The inner and outer diameters of each loop of the figure-of-eight coil with N = 3 turns are 30 mm and 39.6 mm respectively. The coil of which the center is positioned at the origin of an x-y plane can rotate with an angle θ. We calculated the normalized distribution of the x-component of the induced electric field E_x and the activating function ($\partial E_x / \partial x$) in x-y plane at z = 5 mm when the coil is moved along y-axis and rotated in x-y plane.

2) *Calculation of Threshold for Excitation of Nerve Fiber*: The nerve fiber with a diameter of 20 μm with infinite length is positioned parallel to x-axis at z = 5 mm (Fig.1). We apply the modification of the model proposed by J. Roth and J. Basser as shown in Fig.2. In our model, the parameters of the Frankenhaeuser -Huxley myelinated nerve fiber are employed. It has been shown that the maximum inward membrane current $I_{i,n}$ occurring at the negative peak of the activating function ($\partial E_x / \partial x$) causes the initiation of the nerve excitation consequent upon the depolarization of the membrane potential $V_{i,n}$. We simulated the nerve excitation elicited by a monophasic magnetic field. In this simulation, the peak current in the coil is defined as the stimulating intensity. We analyzed the changes of the threshold of the nerve excitation with the y-distance of the center of the figure-of-eight coil in each case of θ = 0, 60, 90° .

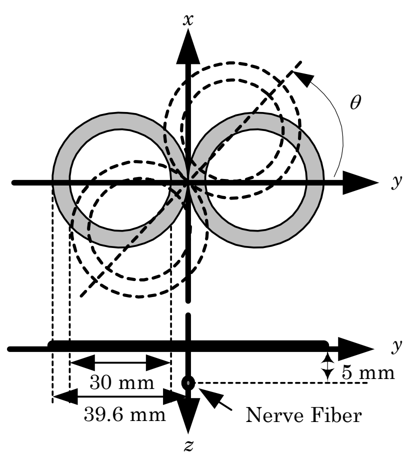

Fig.1 Position of the figure-of-eight coil used in the model of the magnetic nerve stimulation.

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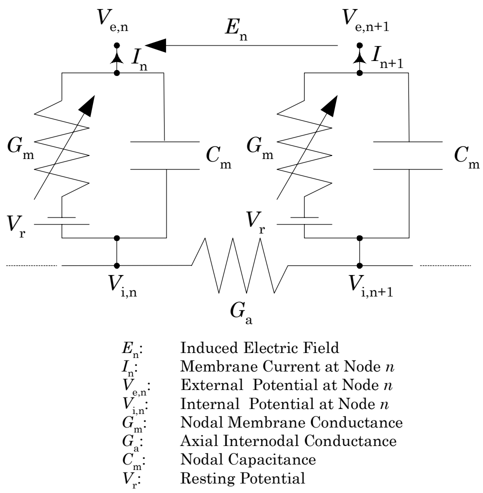

Fig.2 Model of myelinated nerve fiber stimulated with the induced electric field in the magnetic nerve stimulation.

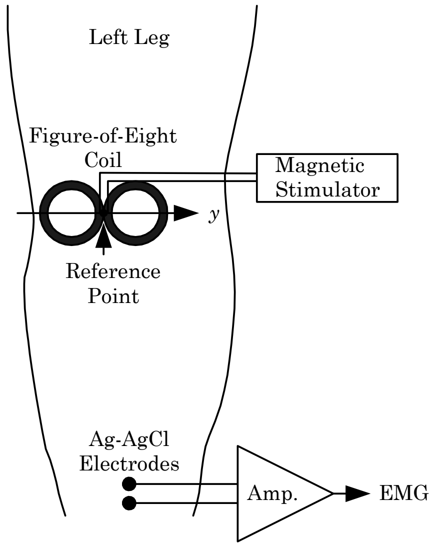

Fig.3 Experimental of the magnetic stimulation of the tibial nerve at the knee of the left leg.

B) *Experimental Study*

The experiment on the magnetic peripheral nerve stimulation was conducted in order to verify the validity of the result of the theoretical calculation. The subject was 22 years old healthy male who gave informed consent. The tibial nerve at the knee of the left leg was stimulated magnetically with a figure-of-eight coil of which the inner and outer diameters are same as the model used in the theoretical calculation (Fig.3). The magnetic stimulator was SMN-1100 (Nihon-Kohden Co.) which generates the magnetic pulse field by the electric current flowing into the coil discharged from a capacitor. The waveform of the magnetic field is monophasic similar to that used in the theoretical calculation. As the intensity of the magnetic field is in proportion to the capacitor voltage, we defined the capacitor voltage as the stimulating intensity in this experiment. The compound muscle action potential (CMAP) from the soleus muscle elicited by the magnetic stimulation was recorded with 10 mm Ag-AgCl recording discs. First, the reference point where the CMAP was elicited with the least stimulating intensity was searched with the figure-of-eight coil of which the junction was parallel to the long axis of the leg (Fig.3). The least stimulating intensity with which CMAP was elicited was inspected with shifting the coil toward lateral direction from the reference point in each case of θ= 0, 60, 90°.

III. Results

A) *Theoretical Calculation*

1) *Calculation of Induced Electric Field and Activating Function*: The x-component of the induced electric field E_x in x-y plane at z = 5 mm in each case of θ = 0, 60, 90° is shown in Fig.4. The E_x is concentrated at the center of the figure-of-eight coil when θ is 0° (Fig.4(a)). When θ is 60°, though the E_x is concentrated at the center of the figure-of-eight coil, the ridge of the E_x is distorted (Fig.4(b)). When θ is 90°, instead of the concentration of the E_x at the center of the figure-of-eight coil, both the highest and lowest points of the E_x are located at the edges of the figure-of-eight coil (Fig.4(c)).

The activating function ($\partial E_x / \partial x$) in x-y plane at z = 5 mm in each case of θ = 0, 60, 90° is shown in Fig.5. As the negative peak of ($\partial E_x / \partial x$) is located on the line of y = 0 mm when θ is 0°, the threshold for excitation of the nerve fiber is expected to be lowest when the nerve fiber is located at y = 0 mm when θ is 0°. When θ is 60°, the negative peaks of ($\partial E_x / \partial x$) are on the lines of y = -26, -6, 24 mm, so the minimum value of the threshold for nerve excitation are expected when the nerve fiber is located at y = -26, -6, 24 mm. When θ is 90°, the negative peaks of ($\partial E_x / \partial x$) on the lines of y = -15, 15 mm indicates that the threshold for the excitation of the nerve fiber in the vicinity of the edge of the figure-of-eight coil is expected to be lowest when θ is 90°.

2) *Calculation of Threshold for Excitation of Nerve Fiber*: Figure.6 shows the changes of the threshold for the nerve excitation with the y-distance of the center of the figure-of-eight coil in each case of θ= 0, 60, 90°. The positions of the coil having the minimum values of the threshold shown in Fig.6 agree with the negative peaks of the activating function ($\partial E_x / \partial x$) shown in Fig.5. When θ is 0°, the threshold is lowest at y = 0 mm, and minimum at y = ±36 mm. When θ is 60°, the threshold become minimum at y = -26, -6, 24 mm. When θ is 90°, the threshold becomes minimum at y = -15, 15 mm. The lowest value of the threshold with θ= 0° (y = 0 mm) nearly equals to that with θ= 90° (y = 15 mm).

C) *Experimental Study*: The least stimulating intensity of eliciting CMAP at the soleus muscle with shifting the coil

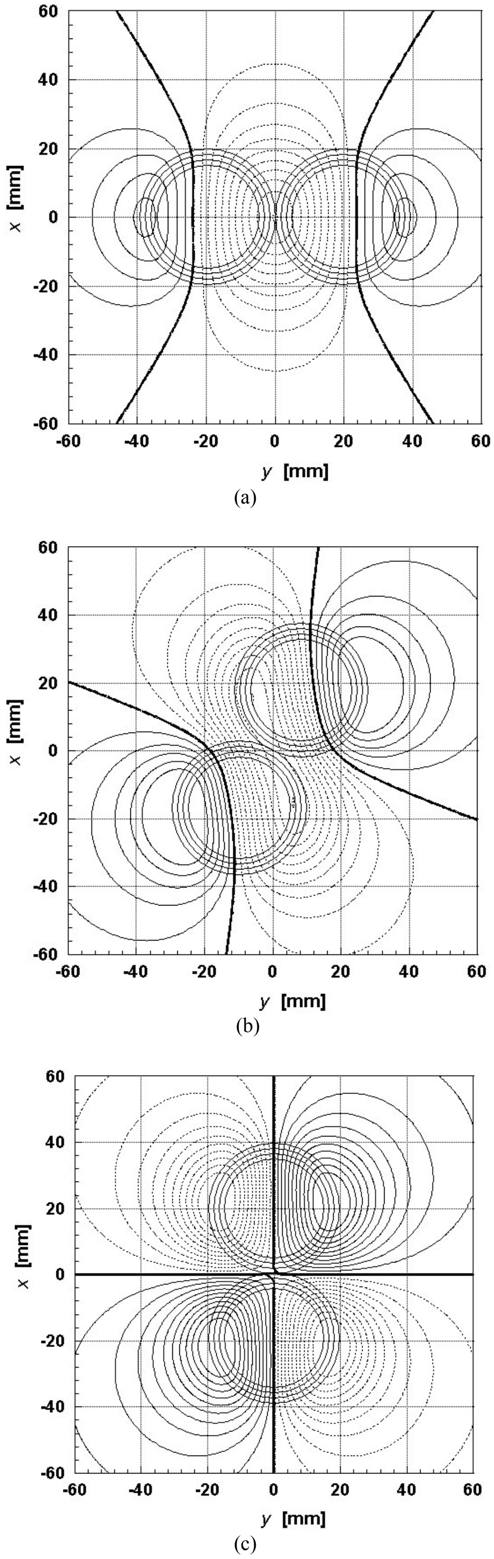

Fig.4 The x-component of the induced electric field E_x in x-y plane at z = 5 mm. The zero contours bold. The positive contours dashed and the negative contours solid. (a) $\theta = 0^\circ$. (b) $\theta = 60^\circ$. (c) $\theta = 90^\circ$.

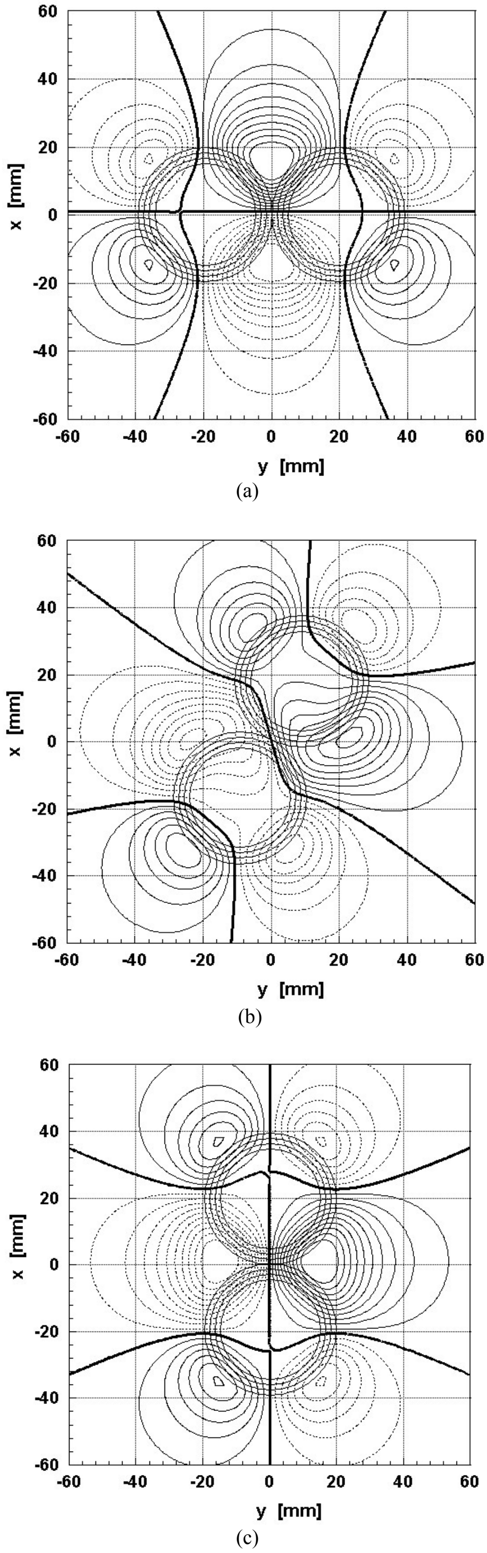

Fig.5 The activating function ($\partial E_x / \partial x$) in x-y plane at z = 5 mm. The zero contours bold. The positive contours dashed and the negative contours solid. (a) $\theta = 0^\circ$. (b) $\theta = 60^\circ$. (c) $\theta = 90^\circ$.

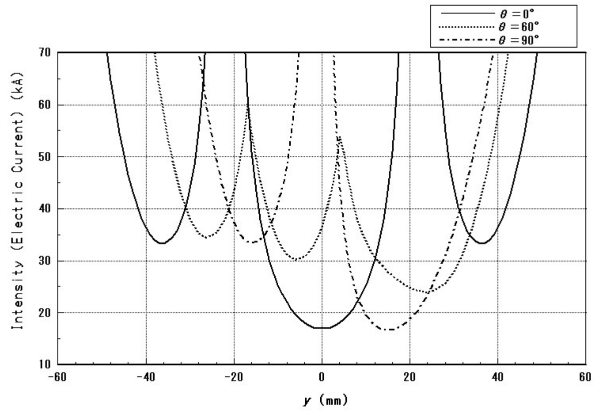

Fig.6 Changes of the threshold for the nerve excitation with the *y*-distance of the center of the figure-of-eight coil calculated with the model of the magnetic nerve stimulation.

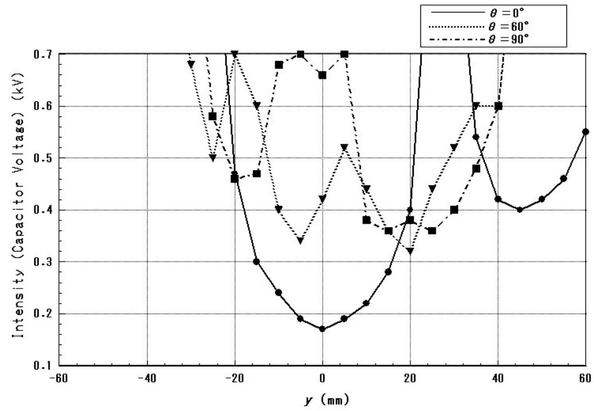

Fig.7 Changes of the least stimulating intensity of the tibial nerve eliciting CMAP at the soleus muscle with the distance from the reference point.

toward lateral direction from the reference point is shown in Fig. 7. As the one wing of the figure-of-eight coil was positioned out of the leg when y < -35 mm, we could not elicit CMAP with the stimulator. The patterns of the least stimulating intensity for eliciting CMAP shown in Fig.7 were similar to the changes of the threshold for the nerve excitation analyzed with the simulation shown in Fig.6. When θ was 0°, the least stimulating intensity for eliciting CMAP was lowest at y = 0 mm, and minimum at y = 45 mm. When θ was 60°, the least stimulating intensity for eliciting CMAP was minimum at y = -25, -5, 20 mm. When θ is 90°, the least stimulating intensity for eliciting CMAP was minimum at y = -20, 15 mm.

IV. DISCUSSION

Some studies argued that the magnetic stimulation of the median nerve in the arm just below the junction of the figure-of-eight coil elicited the largest CMAP when the junction of the figure-of-eight coil was perpendicular to the nerve fiber, which seems to be inconsistent with the theoretical studies using the model of the nerve fiber in the homogeneous medium. Some authors considered that such a discrepancy was due to invalid assumptions in the model including those regarding tissue inhomogeneity. As a human body is composed with tissues with different conductivities such as muscle, fat and bone, the distribution of induced eddy current in the human body is different from that expected from the model using the homogenous medium. The exact distribution of the electric field induced in the arm or leg during the magnetic stimulation of a peripheral nerve is still unknown.

The theoretical study in this paper uses a homogeneous infinite conductor model. The least value of the threshold for nerve excitation at θ= 90° is almost equals to that at θ= 0°. This result is not expected if the nerve is fixed just below the junction of the figure-of-eight coil. The distance between the at θ= 0° and that at θ= 90° is 15 mm, which is a half size of the inner diameter of the figure-of-eight coil. This result indicates that the threshold for the nerve excitation at θ= 90° is likely to be equal to or lower than that at θ= 0° due to the distortion of the induced electric current flowing in the inhomogeneous human body even if the junction of the figure-of-eight coil is located just above the peripheral nerve. It has been indicated that the large negative peak of the activating function was shifted more than the inner diameter of the coil due to the inhomogeneity of the medium.

The experimental study in this paper shows that the patterns of the least stimulating intensity for eliciting CMAP are similar to the changes of the threshold for the nerve excitation analyzed with the simulation. This result supports the validity of the simulation study conducted in this paper. The least stimulating intensity for eliciting CMAP was lowest at θ = 0°, y = 0mm, which is consistent with the most of experimental studies of the magnetic stimulation of the median nerve. We stimulated the tibial nerve at the knee instead of the median nerve at the elbow because the clear pattern of the least stimulating intensity for eliciting CMAP was not obtained with the stimulation of the median nerve. This may be caused by insufficient volume of the arm for the induced current flowing in the arm. Actually, the enough stimulating intensity for eliciting CMAP was not available when the one wing of the figure-of-eight coil was positioned out of the leg, although we used the smaller coil than the commercially available coils. The size of the coil compared to the arm or leg is also considered to be the cause of the discrepancy among the experimental studies of the magnetic stimulation of the peripheral nerve.

V. CONCLUSION

The property of the threshold for the peripheral nerve excitation in the magnetic stimulation is investigated in this paper. By the analysis using the simple model such as the infinite long nerve fiber in the homogeneous medium, we show that the threshold for the nerve excitation become lowest not only when the junction of the figure-of-eight coil is parallel to the nerve fiber but also when that is perpendicular to the nerve fiber.